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Technical Report ARWSE-TR-09009

## **RADIO FREQUENCY (RF) PROPAGATION ALONG SINGLE CYLINDRICAL CONDUCTORS**

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April 2010



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14. ABSTRACT  This report examines the transmission of 10 GHz radio frequency (RF) waves along single cylindrical conductors. Intent is to determine attenuation as a function of distance and conductivity in order to enhance understanding of phenomena related to attachment and transmission of RF to a laser generated plasma filament(s). Attenuation is shown to be highly dependent on conductivity as well as diameter of conductor in some cases providing significant gain over free space propagation. This increase in gain demonstrates promise of a single cylindrical conductor as a transmission mechanism. Data is shown to be relatively consistent with Finite Difference Time Domain modeling for the case of a single cylindrical conductor and open ended waveguide.					
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## SUMMARY

This report contains the experiments and analysis related to the propagation and subsequent rate of attenuation of radio frequency (RF) energy along single conductors. It was demonstrated that RF energy couples to and propagates along, single wire conductors with attenuation improvement over propagation through atmosphere. Materials of various conductivities were examined in order to assess trends of coupling as a function of conductivity, radius, and orientation. These results provide insight into efforts to optimally couple RF energy on to plasma filaments generated by an ultra-short pulsed laser. Additionally, these measurements are used to verify theoretical modeling results. Our investigations were limited to a fixed, short distance and single frequency for this study.

## INTRODUCTION

Electromagnetic (EM) waves of RF are harnessed and used for numerous commercial and military applications. Antennas, standard waveguide, and coaxial transmission line systems are routinely used to broadcast and transport these EM waves. However, RF waves propagating through free space undergo rapid attenuation as these waves disperse as a function of distance from their source. Due to this rapid attenuation, systems that seek to create large power densities at range are very large in size; so large, in fact, that size often becomes the limiting factor.

Recent breakthroughs in the field of ultra-short pulse (USP) lasers have resulted in the capability to form laser generated plasma filaments. These plasma filaments were shown to be conductive (ref. 1) and theoretical investigations have alluded to the possibility of their utility as a conduit for RF energy. It was shown that EM waves can be attached to plasma filaments (ref. 2) oriented as a transmission line. Other techniques, including the creation of a waveguide out of large numbers of filaments, have demonstrated confinement of RF in filament geometries over very short ranges (ref. 3).

In this report, the propagation and subsequent attenuation of RF energy as it travels down varied materials of different conductivities was studied. Transmission of RF waves along single conductors, often referred to as "Goubau" or G-lines (ref. 4), has been a subject of debate. Attenuation for this single conductor case was investigated.

Due to the extremely short lifetimes of the plasma filaments, as well as measurement and triggering requirements, transmission along actual laser generated filaments is often difficult to measure. Useful information can be gathered by studying the dynamics of propagation along surrogates. The surrogate materials used ranged from copper, a highly conductive material, to carbon thread, which has conductivity much closer to the estimated value of laser generated filaments. Through experiments, the attenuation of RF waves once coupled to these surrogates and the phenomena involved with transmission along single transmission lines was observed.

This data will feed directly into understanding the transmission along filaments and aid in the design of future RF-filament coupling experiments.

## METHODS, ASSUMPTIONS, AND PROCEDURES

As in the case of electrical theory, RF waves, in general, will propagate with less attenuation along materials of higher conductivity. The goal was to experimentally verify this improvement in attenuation over distance and prove out the best methods for collecting data.

In the experimental setup (fig. 1), the simplest case of an open-ended, rectangular waveguide fed via an N-connector and driven with a sinusoidal, continuous-wave RF signal at a fixed frequency was examined. The waveguide was placed horizontally perpendicular to the straight, horizontal surrogates. In this arrangement, the dominant electric field is in a transverse-electric mode ( $TE_{10}$ ) with the electric field directed longitudinally along the surrogate. The receiving horn was then placed at 5.08 cm intervals between 5.72 cm and 71.76 cm away from the waveguide, orthogonal to the surrogate with the direction of its feed directed parallel to the conductor.

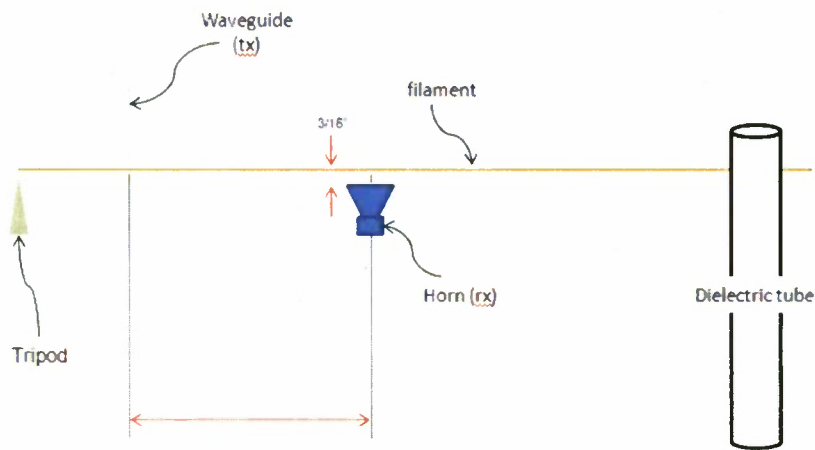


Figure 1  
Experimental setup of single wire transmission line

The chosen range of distances for the receiving horn was determined by the length of the surrogates with the intent to examine primarily the far-field radiation zone. The far-field can be represented by the relation  $\sim 2D^2/\lambda$ , where  $D$  is the largest dimension of the radiator, in this case 28.75 mm for the open ended waveguide. According to this equation, the frequency of investigation  $\sim 10\text{GHz}$ , which corresponds to a wavelength  $\lambda$  of 3 cm, equates to a far-field of  $\sim 5$  cm. The improvement of transmission along these conductors should relate directly to their respective conductivities. A caveat: the conductors used were of varying diameters, which induces an additional frequency dependency that will be discussed in the following section.

Three different materials were used as surrogates in this experiment: a solid copper rod with a diameter of approximately 9.84 mm, a solid aluminum rod ( $\sim 6.15$  mm), and carbon thread (made of strands of carbon fiber,  $\sim 1$  mm). The metal rods were sanded and polished to provide the cleanest surface for coupling and the carbon thread was stretched taut to remove any sagging that would negatively affect coupling.

## RESULTS AND DISCUSSION

Upon examination of the coupling of the surrogates in contrast to the free space measurement, it becomes apparent that the EM waves are in fact coupled and transmitted along the conductor - the scenarios in which surrogates were used show substantial attenuation improvement over the free space scenario. The graph in figure 2 represents S21 data measured on a Vector Network Analyzer, which relates the change in gain of the received signal as a function of frequency. General trends in this case are being looked for, and it can be seen that the initial coupling is much higher to the copper and aluminum rods than to the carbon thread. At the final points, the carbon thread begins to approach the free space value falling within the range of error.

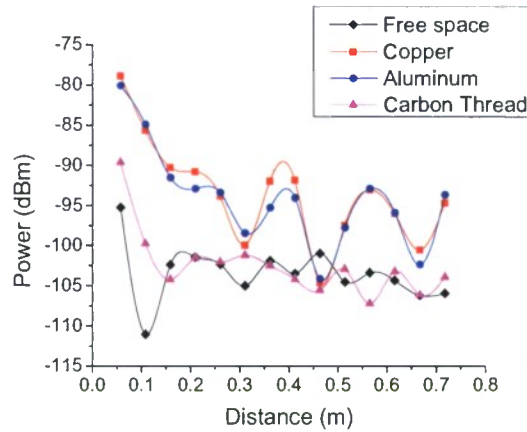


Figure 2  
Non-normalized data from single wire transmission line

It may be more pertinent to interpret this data after the S21 values have been normalized by subtracting the free space case in order to examine the improvement that each conductor presents over free space propagation from the end of the open-ended waveguide (fig. 3). Here, power levels in dB represent relative gain of received signal with the conductor present.

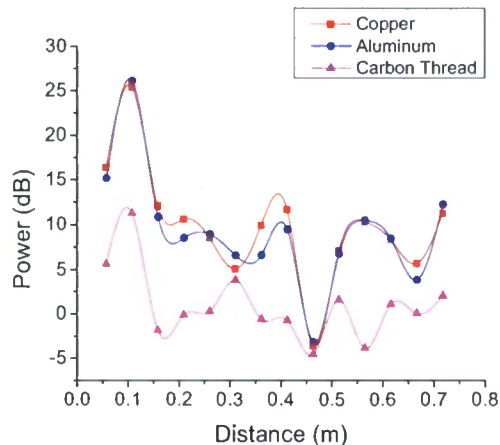


Figure 3  
Data from single wire transmission line normalized over free space

Figures 4 and 5 represent modeling and experimental results for the cases of the copper conductor and the carbon thread, respectively, over a short range. Modeling was performed using Xfdtd by Remcom and carried out by Pegasus LLC. More modeling will be done in order to optimize future coupling orientations for best possible propagation.

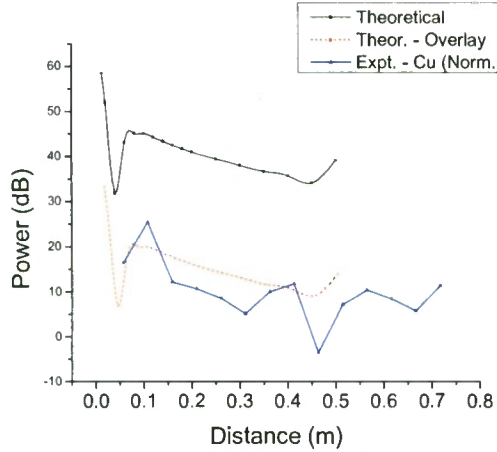


Figure 4  
Overlay of theoretical FDTD model and  
experimental data (copper)

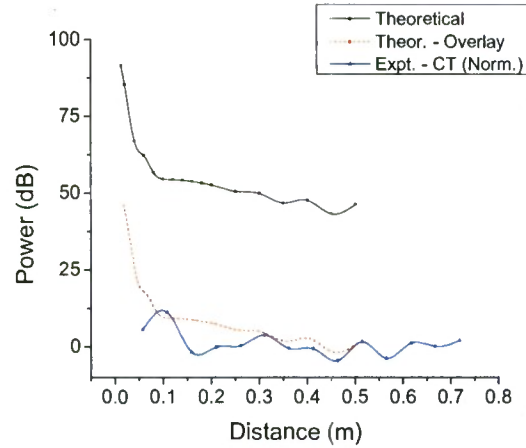


Figure 5  
Overaly of theoretical FDTD model and  
experimental data (carbon thread)

## CONCLUSIONS

After an initial coupling loss (not optimized for these experiments), the data demonstrates radio frequency (RF) energy coupled to single cylindrical conductors and propagated as predicted, achieving attenuation less than that of its free space counterpart propagating through the atmosphere. Conductivity also appears to have a direct impact on the rate of attenuation along a conductor. Additionally, coupling and attachment were observed to be highly dependent on RF frequency and conductor diameter.

The conductivity of carbon thread was calculated to be on the order of  $8124.3 \text{ S/m}^1$ , which is similar to that of a laser generated filament  $353.7 \text{ S/m}$  (ref. 1)<sup>2</sup> in comparison to metals. Carbon thread attenuation was only found to be marginally better than free space under these conditions, most likely due to the non-uniformity of the material (comprised of three large strands) and relatively small diameter compared to the RF frequency. Predictions for transmission along plasma filaments and plasma filament bundles are significantly higher than for the experimental case of the carbon filament. Unfortunately, the range of our study was limited to less than 1 m due to the available length and fragility of the carbon thread; therefore, its utility as a surrogate may be limited for this application.

<sup>1</sup>The conductivity was found by taking the inverse of the resistivity  $\rho$  that is equal to  $\pi r^2 R/L$ , where  $r$  is radius,  $R$  is measured resistance, and  $L$  is length of the thread.

<sup>2</sup>The radii of the carbon thread and referenced filament differ by one order of magnitude.

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